

# Combustion of Shock-Dispersed Fuel in a Chamber

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## Combustion of Shock-Dispersed Fuel in a Chamber

Paper contribution to the  
11th International Symposium on  
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## Combustion of Shock-Dispersed Fuels in a Chamber

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### Abstract

In previous studies we have investigated after-burning effects of a fuel-rich explosive (TNT). In that case the detonation only releases about 30 % of the available energy, but generates a hot cloud of fuel that can burn in the ambient air, thus evoking an additional energy release that is distributed in space and time. The current series of small-scale experiments can be looked upon as a natural generalization of this mechanism: a booster charge disperses a (non-explosive) fuel, provides mixing with air and – by means of the hot detonation products – energy to ignite the fuel.

The current version of our miniature Shock-Dispersed-Fuel (SDF) charges consists of a spherical booster charge of 0.5 g PETN, embedded in a paper cylinder of approximately 2.2 cm<sup>3</sup>, which is filled with powdered fuel compositions. The main compositions studied up to now contain aluminum powder, hydrocarbon powders like polyethylene or sucrose and/or carbon particles. These charges were studied in three different chambers of 4-l, 6.6-l and 40.5-l volume.

In general, the booster charge was sufficient to initiate burning of the fuel. This modifies the pressure signatures measured with a number of wall gages and increases the quasi-static overpressure level obtained in the chambers. On the one hand the time-scale and the yield of the pressure rise depend on the fuel and its characteristics. On the other hand they also depend on the flow dynamics in the chamber, which is dominated by shock reverberations, and thus on the chamber geometry and volume. The paper gives a survey of the experimental results and discusses the possible influences of some basic parameters.

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## Introduction

For about two decades the experimental fluid dynamics group of the Ernst-Mach-Institute has investigated blast phenomena caused by detonating charges in laboratory scale. The in-house development of reliable HE-charges in the mass range of 1 g explosive rendered tests at such a small scale feasible. However, the size of these charges, which are ignited by the means of a high voltage discharge, limits the choice of the explosive material to PETN, a fair enough choice for the investigation of classical blast effects like blast attenuation and blast loads on structures. In the last years the topics of interest have broadened and include explosion-induced combustion phenomena. This subject area can be roughly divided into two sub-topics: combustion as a collateral effect of a charge detonation, when flammable materials are subjected to the blast, and combustion as an inherent effect of the explosive or the charge. Representative for the latter is the issue of after-burning of TNT. Bomb calorimetric tests have shown that in the case of TNT the heat of detonation is around 4.6 kJ/g, while the heat of combustion is 15.026 kJ/g [1]. The reason for this difference is the strong oxygen deficiency of TNT, i.e., the detonation products consist to a large extent of species that are not completely oxidized.

This gives rise to the question whether and how the after-burning energy contributes to the blast effects of a TNT-charge detonating in air. A prerequisite for the release of the after-burning energy is that the detonation products are mixed with ambient air. Thus the mixing rate (and in consequence the dynamics of the flow-field caused by the detonation) is one of the fundamental parameters governing the combustion processes. Nevertheless, to be actually ignited the mixture has to contain energy in excess of an activation threshold, at least locally. The necessary energy is initially inherent in the hot detonation products, but expansion cools the products cloud while it is being mixed with ambient air. Hence the balance between cooling rates and the mixing and burning rates governs to which degree the after-burning energy is converted. The existence and the geometry of a confinement can modify the energy release in a multitude of ways: it can constrain the expansion of the products cloud, it can give rise to blast reflections and spots where interacting blast waves reheat the mixture of the products and air beyond the ignition threshold and it shapes the evolution of the flow-field thus influencing the mixing.

PETN exhibits negligible after-burning. It is well, albeit not perfectly, oxygen balanced. Its heat of detonation amounts to 6.28 kJ/g, which is 76.5% of its heat of combustion, the value being 8.19 kJ/g [1, 2]. To enhance the after-burning effects EMI has designed a composite charge consisting of a spherical core of PETN embedded into an outer shell of solid TNT. By the means of this charge it was feasible to study after-burning in different geometries. Some results will be presented below.

However, the main topic is a series of small-scale experiments that can be looked upon as a natural generalization of the after-burning concept. The basic idea behind this generalization is: if combustion is to be considered as a relevant energy source in the aftermath of a charge detonation, it is not necessarily the detonation products from the explosive that have to constitute the fuel. Other flammable (non-explosive) substances might generate similar effects when dispersed by a detonation. The effects could even be more pronounced, since a number of substances outmatch TNT in terms of the heat of combustion. This line of thought led to the development of what we call Shock-Dispersed-Fuel (SDF) charges. The design of this charge type will be discussed below.

## Charge Design

The basis of all charge types discussed in this paper are our spherical small-scale PETN-charges. They consist of nearly pure PETN at a density of about  $1 \text{ g/cm}^3$ . Two electrical ignition wires are embedded. The small gap between these wires is bridged by a thin resistance wire at the top. Care is being taken that the resistance wire is located in the center of the explosive sphere. A high voltage discharge explodes the bridge wire. This explosion drives the detonation through the charge. In laboratory experiments we typically use charges with masses from 0.2 g to approximately 1.5 g.

A spherical PETN charge of 0.5 g constitutes the core of the composite TNT-PETN charge. The core is repeatedly dipped into molten TNT and dried. Thus an outer shell of TNT forms. Its density is also around  $1 \text{ g/cm}^3$ . For our experiments charges with three different shell masses were manufactured: 0.5 g, 0.7 g and 1 g.

The SDF charges finally consist of a lightweight paper cylinder with a height and diameter of 14 mm. Again a spherical PETN charge of 0.5 g is inserted into the center of the cylinder. It acts as the dispersing booster. The remaining volume ( $1.6 \text{ cm}^3$ ) of the cylinder is filled with the fuel to be dispersed. The fuels of our choice for this exploratory test series were readily available powders of aluminum, hydrocarbons like sucrose (labeled HC in plots) or polyethylene (PE), carbon or mixtures of these. The cylinder holds fuel masses from 0.65 g to 1.1 g depending on the density of the powders. We have also substituted these non-explosives fuels by PETN or TNT powder.

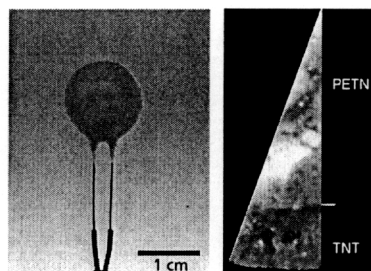


Figure 1

Left: Photograph of the TNT-composite charge. Right: Fragment of an accidentally broken composite charge. The white zone consist of PETN, the ochre zone of TNT. In between an intermediate zone is visible where the TNT has diffused into the PETN layer.

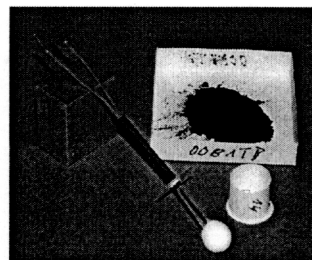
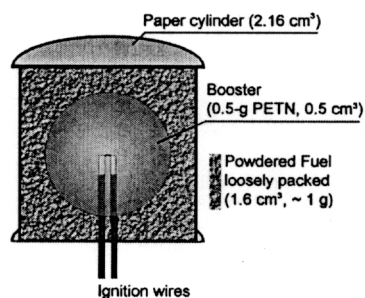


Figure 2

Left: Schematic sketch of the SDF charge design.

Right: Photograph of the charge components (booster, paper cylinder and powder filling, here carbon powder).

Particulate size is certainly an aspect that plays an important role in the combustion of the dispersed fuels. The aluminum powder came in form of thin flakes (thickness in the order of  $2\text{ }\mu\text{m}$ ) with a wide distribution of sizes seen in the SEM image in Figure 3. The coarsest powder was polyethylene (PE) with granules ranging from  $0.1$  to  $1\text{ mm}$  in diameter (Figure 4). According to the manufacturer the average particle diameter is around  $350\text{ }\mu\text{m}$ .

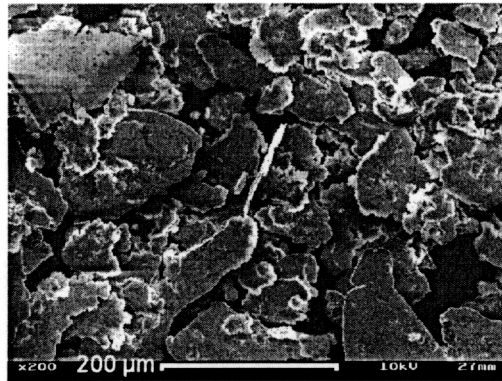


Figure 3  
SEM image of the aluminum flakes.

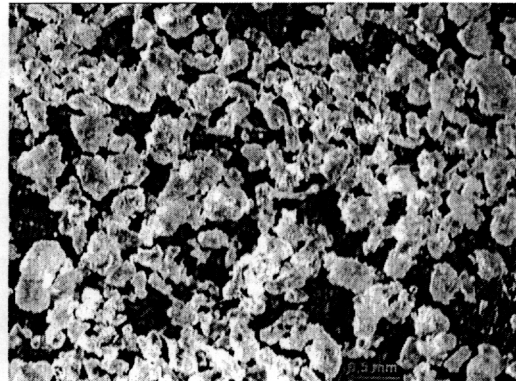


Figure 4  
Microscopic image of the PE granules.  
(Red marker:  $500\text{ }\mu\text{m}$ ).

## Experiments and Results

Initial experiments were carried out in a rectangular chamber of about  $4\text{ l}$  inner volume. The chamber dimensions are  $101.5\text{ mm} \times 101.5\text{ mm} \times 386\text{ mm}$ . Steel plates formed the end-walls, the bottom and the roof, whereas the side-walls were manufactured from transparent Macrolon plates, thus giving optical access to the set-up. The chamber was equipped with a number of piezo-electric pressure gages. In addition, we monitored the chamber by the means of a high-speed video camera. The SDF charges were detonated near the center of the chamber. Figure 5 shows a photograph of the set-up.

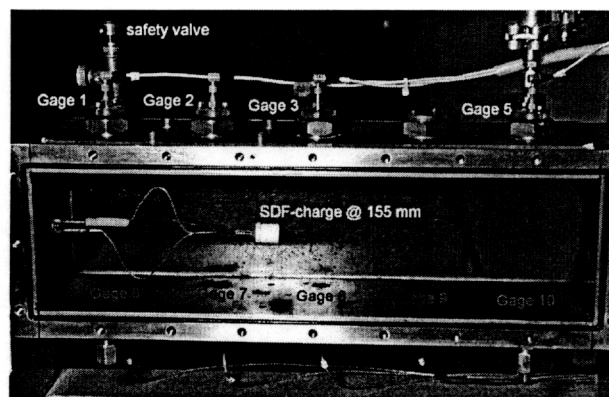


Figure 5  
Photograph of the  $4\text{-l}$  chamber.  
(Front window removed).

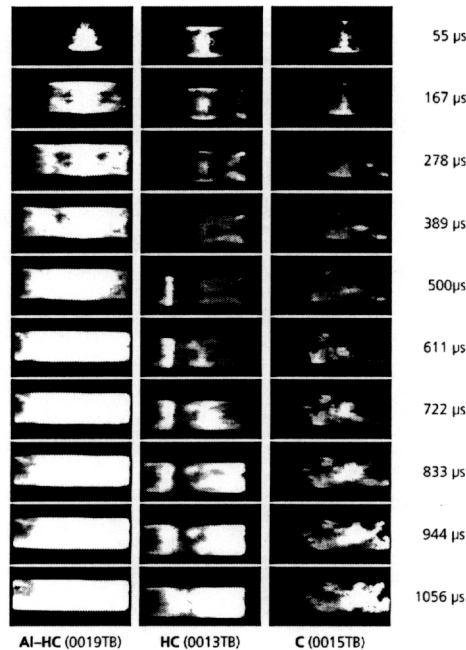


Figure 6  
Series of video frames showing the combustion of three types of shock-dispersed fuel in the 4-l chamber.

Figure 6 shows three examples from the video coverage of the tests. The frames in the left column originate from a test on a mixture of aluminum and sucrose. This mixture appears to be rapidly ignited and the flame spreads over essentially the whole volume of the chamber within 400  $\mu$ s. A test on pure sucrose powder yielded a somewhat different result (middle column): though the detonation initially creates a hot luminous region near the charge, the luminosity decreases during the first 400  $\mu$ s. After 500  $\mu$ s the luminosity suddenly increases in a strongly localized region in the left half of the chamber. Presumably this region coincides with the location of a strong interaction between reflected shocks, which compress and reheat this zone. A second luminous zone develops on the right hand of the chamber. Later on both luminous region grow in size, merge and finally also spread over nearly whole chamber. The third column shows a test on carbon powder. Again the luminosity initially decreases until two hot spots form at 600  $\mu$ s. Though this sets forth combustion, the flame spread is much slower than in the cases of the sucrose powder and the aluminum-sucrose mixture. Nevertheless, the video sequences indicate that it is possible to ignite the fuel from the SDF charges.

The next question to answer is what pressure effects go along with the combustion. In a confined situation one effect is for certain: an increase of the quasi-static pressure in the chamber. Figure 7 thus shows overpressure records from the test chamber for a period of 20 ms. It includes the results from four tests with different SDF charges and for a test where the bare booster charge was detonated. The initial shock dynamics create large pressure peaks of up to 20 bar, which deteriorate the readability of the graph. Hence we low-pass filtered the data. At a cut-off frequency of 2 kHz remainders of the shock reverberation structure are still fairly pronounced, a cut-off frequency of 0.5 kHz provides smoother curves, but sets a lower limit of 700  $\mu$ s to the apparent the rise time. Anyhow, the figure proves that all SDF charges generate overpressures in excess to those originating from the booster. The mixture of aluminum and sucrose generates the largest overpressure and the steepest pressure rise. The maximum in the quasi-static overpressure is attained in less than 3 ms. Pure carbon powder yields the lowest overpressure and a comparatively slow pressure rise; it takes about 15 ms until the maximum is obtained.

Analysis shows that the 4-l chamber contains too little oxygen for complete combustion of the shock-dispersed fuels with exception of the aluminum-sucrose mixture. Even this mixture would consume about 94% of the available oxygen. Thus incomplete combustion is either certain or very likely to occur in all tests. However, one can get a rough idea about the degree of energy conversion from the maximum level of quasi-static overpressure found in the experiments.



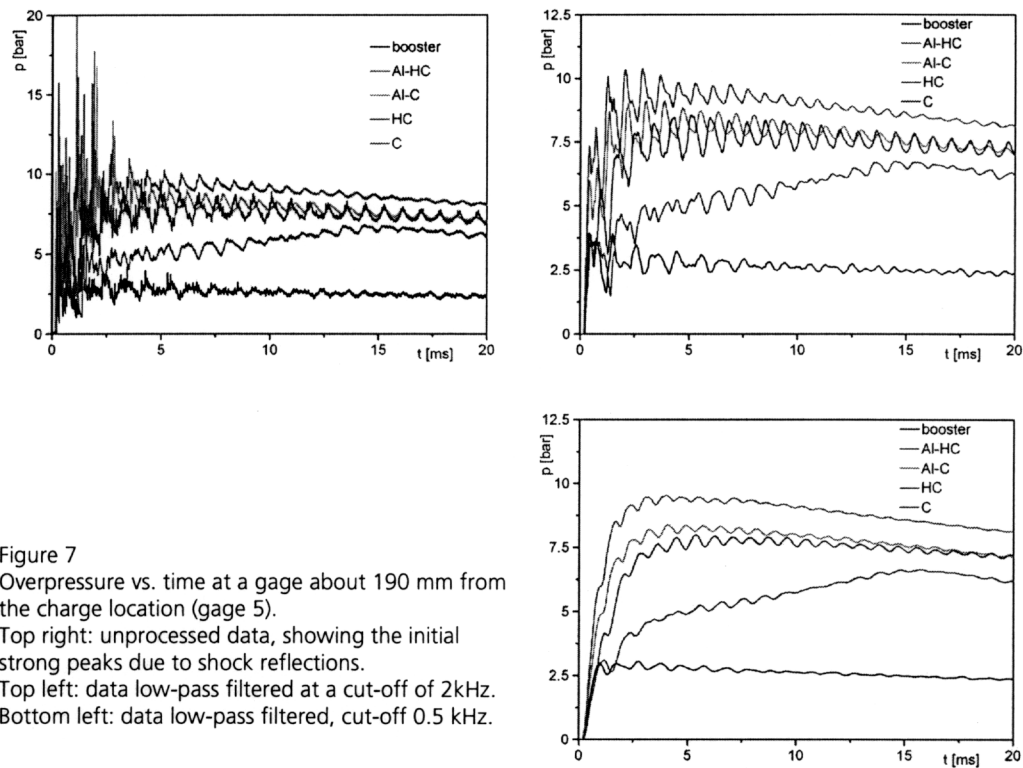


Figure 7

Overpressure vs. time at a gage about 190 mm from the charge location (gage 5).

Top right: unprocessed data, showing the initial strong peaks due to shock reflections.

Top left: data low-pass filtered at a cut-off of 2 kHz.

Bottom left: data low-pass filtered, cut-off 0.5 kHz.

In the case of the aluminum-sucrose mixture the level found in the experiments is about 9.2 to 9.4 bar. A theoretical estimate for the maximum possible overpressure can be given on the following basis: We assume the correct amounts of PETN, aluminum, sucrose and air to be well mixed throughout the chamber and calculate the pressure at the state of a constant-volume explosion [3]. This can readily be done by the means of a thermo-dynamic equilibrium code. The result for the SDF charge containing the aluminum-sucrose mixture amounts to about 11.5 bar. The experimental value is about 20% below this theoretical maximum. Thus we are sure that a major amount of the fuel has been oxidized.

The smoothed pressure records from Figure 7 give an upper estimate for the time-scale necessary for the combustion to become fully effectual. Figures 8 and 9 try to give an impression on the efficiency of the combustion during the first 250  $\mu$ s. The plot in Figure 8 shows the time-of-arrival of the primary blast versus the distance from the charge center. SDF charges containing pure carbon or sucrose powder arrive retarded at the gages: the paper cylinder filled with the fuel initially acts as a containment. This effect is less pronounced for SDF charges containing mixtures with aluminum powder. At a distance of 200 mm the blast catches up with the blast from the bare booster. Similar effects can be seen in Figure 9, which presents the peak overpressure values versus the range. Close to the charge the peak overpressures are smaller than for the bare booster (containment effect). At distances of 125 mm and 200 mm the charges containing the aluminum-sucrose mixture already generate somewhat higher peak

pressures than the bare booster, while the charges containing pure sucrose or carbon powder become approximately equivalent to the bare booster at a distance of 200 mm, i.e., after about 250  $\mu$ s. Thus we conclude that for SDF charges containing aluminum powder the combustion switches in fairly early and provides some additional energy already within the first 250  $\mu$ s. Figure 10, a time-resolved plot of the local pressure at a gage 190 mm from the charge, exemplifies the further development for the aluminum-sucrose mixture.

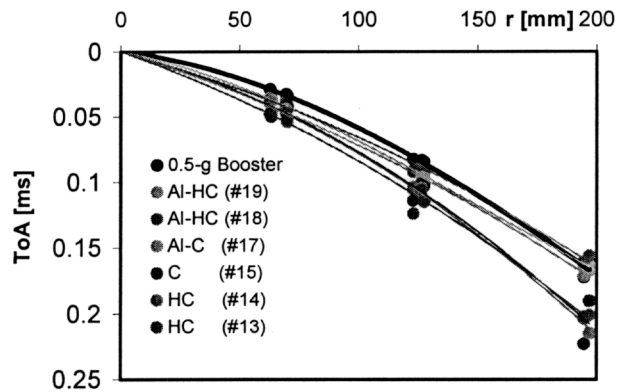


Figure 8  
Time-of-arrival for the incident blast from SDF charges compared to the booster.

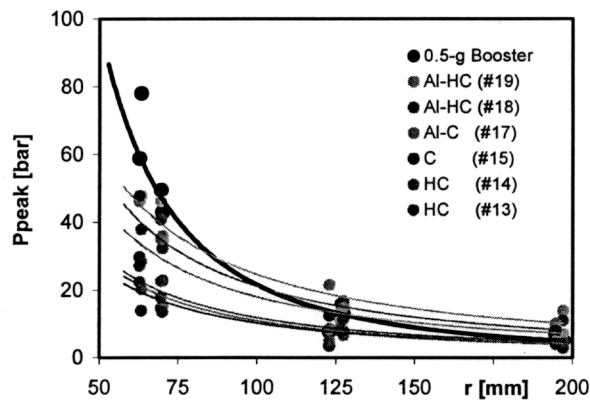


Figure 9  
Peak overpressure for the incident blast from SDF charges compared to the booster.

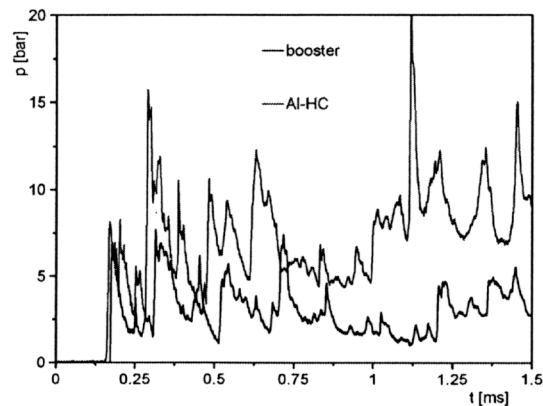


Figure 10  
Time-resolved overpressure history for an SDF charge containing aluminum and sucrose compared to the bare booster. Gage distance from charge 190 mm.

Similar tests were performed in a cylindrical vessel of 6.6-l volume (inner diameter 200 mm, height 210 mm). This vessel provides 65% more oxygen and thus increases the chances for complete combustion. Figure 11 compares three pressure records from this test series, namely for the detonation of a bare 0.5-g booster, for a composite TNT-PETN charge with a solid shell of 1g TNT and for an SDF charge filled with 1 g pure aluminum powder. The pressure records are again low-pass filtered at a cut-off frequency of 2 kHz. Theoretical pressure levels for the state of constant-volume explosion are included (green lines). It is obvious that energy from the combustion of aluminum rapidly contributes to the pressure in the vessel. Most of this energy is released within the first 1.5 ms after the detonation. The finally attained pressure level is close to the theoretical expectation. In terms of the quasi-static pressure the yield from one gram of aluminum flakes exceeds the composite TNT charge with 1 g solid TNT by about 30%.

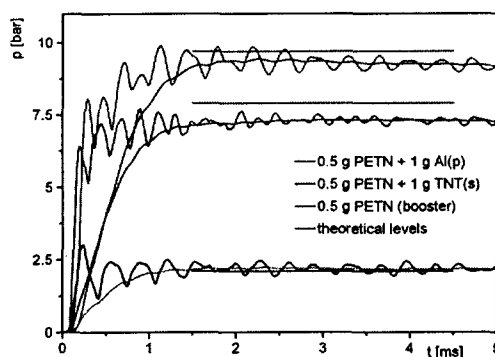


Figure 11  
Overpressure vs. time in the cylindrical 6.6-l vessel for three charges: the bare booster, a composite charge and the SDF charge containing 1 g Al-flakes. The records are low-pass filtered at a cut-off frequency of 2 kHz. Also included: data filtered at 0.5 kHz. This filtering smoothes the oscillations, but falsifies the initial pressure rise rate.

A variety of fuel compositions was studied in the 6.6-l vessel. Figure 12 summarizes the maximum overpressure levels attained with different compositions and compares them to the energy content of the SDF charges (in terms of total heat of combustion). In general, charges that contained aluminum flakes yielded overpressure levels above that of the composite TNT charge and burned comparatively rapidly. Pure carbon powder also supplied some additional pressure in excess of that from the composite charge, but combustion always started very slowly and the burning rates varied to a large extent. Thus it took periods from 20 to 40 ms, before the maximum overpressure level was attained. Adding some aluminum flakes (10% of the mass) to the carbon powder increased the burning rate considerably and brought down the combustion period to 10 ms. The pure polyethylene granulate also combusted fairly slowly: the main combustion period took about 12 ms. The relatively low overpressure level of 5.7 bar (compared to a theoretical expectation around 10.3 bar) indicates incomplete combustion. One reason is that the stoichiometric combustion of PE consumes large amounts of oxygen, so even the 6.6-l vessel again contains too little air. In addition, the PE granules were rather coarse; smaller particulate sizes could cause more rapid and complete combustion.

Another note on Figure 12: one might notice that by bringing up the heat of combustion by 90% one only yields a 30%-increase in the quasi-static overpressure. The pressure increase in the chamber is strongly related to the average temperature and at elevated temperatures the heat capacities of the products increase. Thus more energy is needed to bring the pressure further up. The effect is exemplified in Figure 13, a result from a thermodynamic equilibrium calculation of the constant-volume explosion of pure TNT in the 6.6-l vessel.

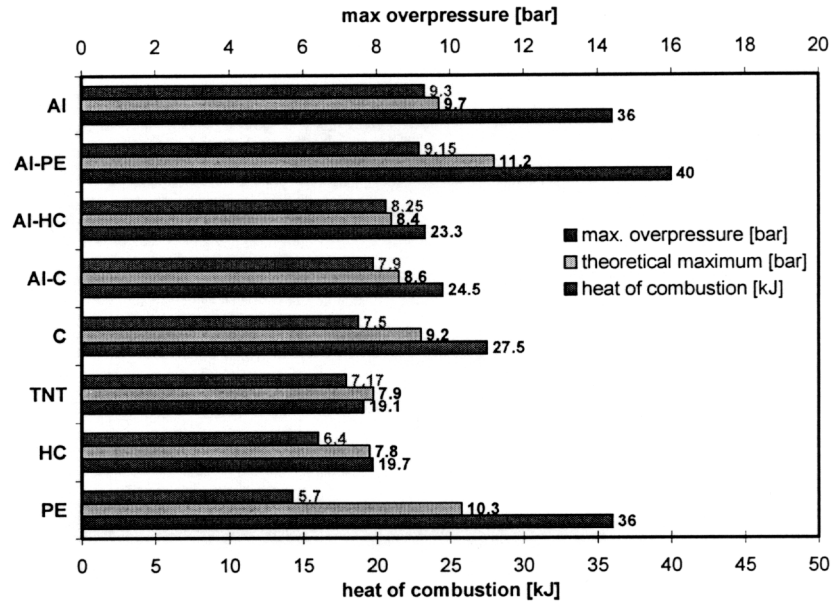


Figure 12

Diagram of the experimentally observed quasi-static overpressure levels for SDF charges (blue) in the 6.6-l cylindrical vessel. For comparison the theoretical expectation (gray) and the total heat of combustion of the charges (red, bottom scale) are included.

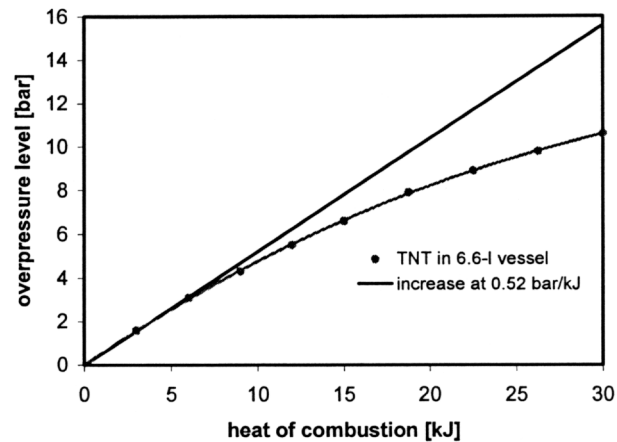


Figure 13

Result from a thermo-dynamic equilibrium calculation of the constant-volume explosion of TNT in a 6.6-l vessel filled with air. The graph displays the overpressure level attained as a function of the heat released. At ambient conditions 2kJ suffice to increase the pressure by 1 bar, at a level of 10 bar (and a corresponding temperature of 2800 K) approximately 4.5 kJ are necessary for a further 1-bar increase.

A couple of tests were repeated in a cylindrical vessel of 40.5-l volume. The dimensions of this cylinder are about twice the dimensions of the 6.6-l cylinder: the diameter is 369 mm, the height 379 mm. Thus the typical frequency of the shock reverberations in the vessel is smaller and the products/fuel clouds can expand further. In addition, the larger volume of inevitably calls for lower levels of the quasi-static pressure. Figure 14 gives a summary of the observed levels for different SDF charges. Only charges containing aluminum flakes yielded pressure levels in excess of the level caused by a composite TNT charge. Fillings of pure sucrose and carbon powder did not give any additional energy release beyond that from the booster charge, so we have to assume that ignition essentially failed. The performance of PE was again far from the theoretical expectation.

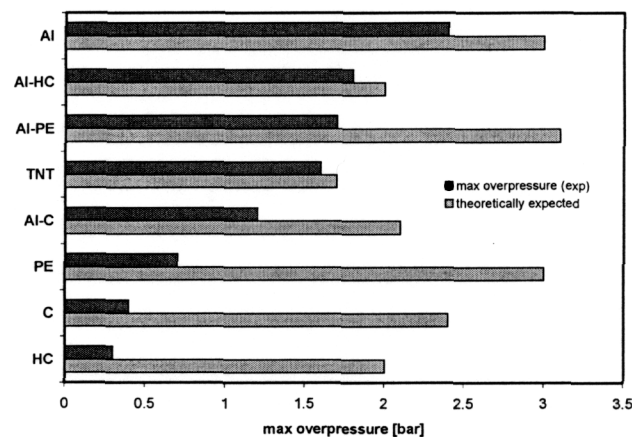


Figure 14

Diagram of the experimentally observed quasi-static overpressure levels for SDF charges (blue) in the 40.5-l cylindrical vessel. For comparison the theoretical expectation (gray) is included.

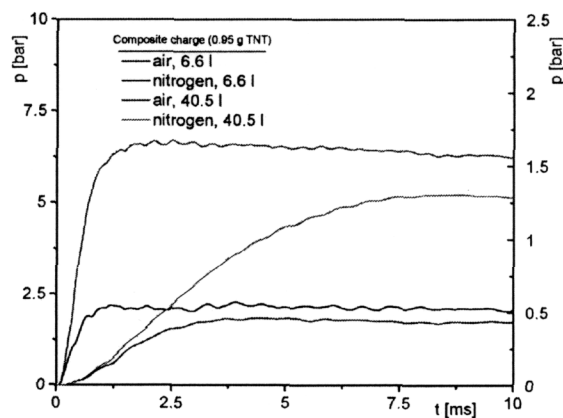


Figure 15

Development of the quasi-static overpressure in the 6.6-l vessel (left scale) and 40.5-l vessel (right scale). Tests with composite TNT charges. Data are low-pass filtered at 0.5 kHz for the tests in 6.6-l vessel and at 0.1 kHz for the tests in 40.5-l vessel due to the lower frequency of shock reverberations.

To attain the maximum pressure levels it took a longer period ranging from 5 to 10 ms in the 40.5-l vessel. The same effect was found in the studies on the after-burning of TNT. Figure 15 shows a diagram from this study. Tests with composite charges were performed in the 6.6-l and the 40.5-l vessel for two cases: the vessels filled with air at ambient pressure or – to inhibit the after-burning – with nitrogen. The plot does not only show the difference in the quasi-static overpressure levels due to the after-burning energy, it also gives an idea of the release rates: in the 6.6-l vessel the maximum pressure in air is attained within the first 1.5 ms, while this takes about 7.5 ms in the 40.5-l vessel. The basic reason is that the faster and more intense shock reverberation in the smaller vessel efficiently enhance the mixing between the detonation products and the air in the vessel. This decrease of the after-burning rates with increasing linear dimensions of the confinement has also been found in numerical simulations [4, 5]. We expect a similar effect on the performance of SDF charges.

## Summary

The experiments show that shock-dispersed fuels will combust in many cases. They are most effective in narrow confinements, where shock reverberations enhance the mixing between fuel and air, which is an important parameter controlling the burning rate. The largest effects were observed for fuels that consist or at least contain an appreciable amount of aluminum flakes. This might in part well be due to the size and form of the flakes. In terms of the quasi-static overpressure obtained in the chambers 1 g of the aluminum flakes excels 1 g of TNT. Nevertheless, a sufficient supply of air is a prerequisite for combustion to become effective. Thus in too small a confinement lack of oxygen can terminate the energy release prematurely.

Larger confinements in some cases caused a failure to ignite the fuel. The current hypothesis is as follows: the detonation products cloud and the dispersed fuel cloud can expand further and thus cool beyond the ignition threshold, before blast reflections from the walls can provide sufficient mixing with the ambient air. The details nevertheless depend also on the fuel: aluminum flakes or a mixture of aluminum flakes and sucrose yielded overpressure levels close to the theoretical limit even in the 40.5-l vessel. Thus it has to be analyzed whether the poor performance of polyethylene for example correlates to the properties of the substance itself or to the size and shape of our test specimen.

Since the burning rates decrease with the linear vessel dimensions, it has to be anticipated that SDF charges might have little or no associated additional pressure effects in free-field detonations. Mixing in this case is mainly provided at the boundary of the products/fuel cloud and the ambient air and is only enhanced by instabilities of this boundary. To couple energy into the peak pressure or into the impulse of the blast wave the additional energy has to be released fairly fast. Thus we expect that the main effect of SDF charges in free-field are enhanced temperatures in the fire-ball, though we cannot completely rule out associated pressure effects on the basis of the current experimental findings.

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